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Customized Dynamic Splinting: Orthoses that Promote Optimal Function and Recovery after Radial Nerve Injury: A Case Report

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ABSTRACT: Radial nerve injury is a relatively common occurrence and recovery depends on the level of injury and extent of connective tissue damage. Orthoses (splints) are often provided to compensate for lost motor power. This article chronicles the recovery, over 27 months, of a 76-year-old woman who sustained a high radial nerve injury of her dominant arm during surgery for total shoulder replacement (Delta Reverse). Customized, low-profile dynamic splints, unlike any previously published design, were developed to address her goals for functional independence and the biological needs of the tissues. Dynamic power was provided to the wrist, fingers, and thumb by elastic cords and thin, flexible thermoplastic, without the need of an outrigger, thus avoiding the need for wire bending and cutting. At the outset, the splint was forearm-based and when wrist extension power was recovered, a hand-based splint was designed. Eventually, a circumferential hand-based thumb-stabilizing splint fulfilled most of the remaining orthotic requirements.

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RADIAL NERVE ANATOMY AND INNERVATION

The radial nerve has a long course, beginning in the neck as a branch of the posterior cord of the brachial plexus with contributions from C5, C6, C7, C8, and T1, and dividing near the elbow, into its two terminal branches—the (motor) posterior interosseous nerve (PIN) and the dorsal sensory radial nerve (DSRN) (Figure 1).[1,2] It fully innervates all extensors distal to the shoulder, except the lumbricals and interossei, which are the principle extensors of the finger interphalangeal (IP) joints. Thus, the radial nerve powers the muscles that extend the elbow, wrist, finger metacarpalphalangeal (MCP) joints and thumb.[3] It also innervates the supinator muscle, which along with biceps brachii, supinates the forearm. It has a small contribution to the strength of elbow flexion through its innervation of the brachioradialis. Unlike the median and ulnar nerves, the radial nerve innervates no intrinsic hand muscles.

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RADIAL NERVE INJURY

Etiology

The radial nerve is reputedly the most frequently injured major nerve in the upper extremity.[3] Mechanisms of injury include humeral fracture, laceration, missiles, injections, traction, shoulder or elbow joint dislocations, and compression.[3−5] Compression can occur as a result of external forces such as pressure from crutches, or internal forces causing nerve entrapment.[6] Surgical procedures have caused 1) partial or complete transection, 2) compression or traction due to intraoperative positioning of the upper limb, and 3) compression from a tourniquet.[3,7] Less commonly, neuritis, tumor, diabetes, or leprosy can cause radial nerve impairment.[3]

Functional and Biological Consequences

Radial nerve palsy is characterized by wrist drop (Figure 3A), a posture of the hand caused by paralysis of the wrist extensors, which prevents the natural tenodesis action that enables power grasp and

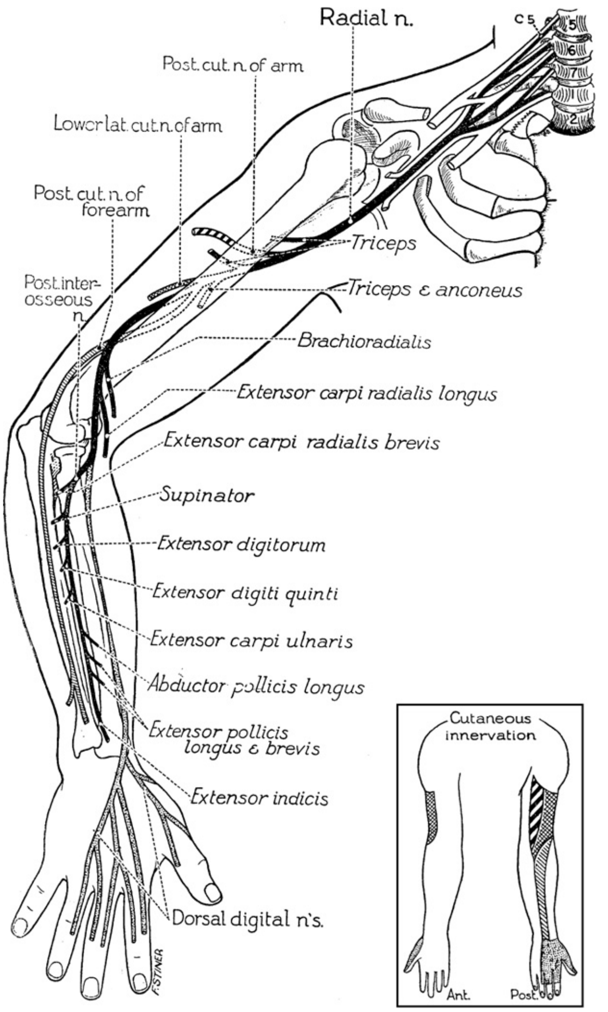

FIGURE 1. *Course and distribution of the radial nerve. (From Haymaker and Woodall,[2] with permission.) Tenodesis grasp occurring during approach and grasp of an object.*

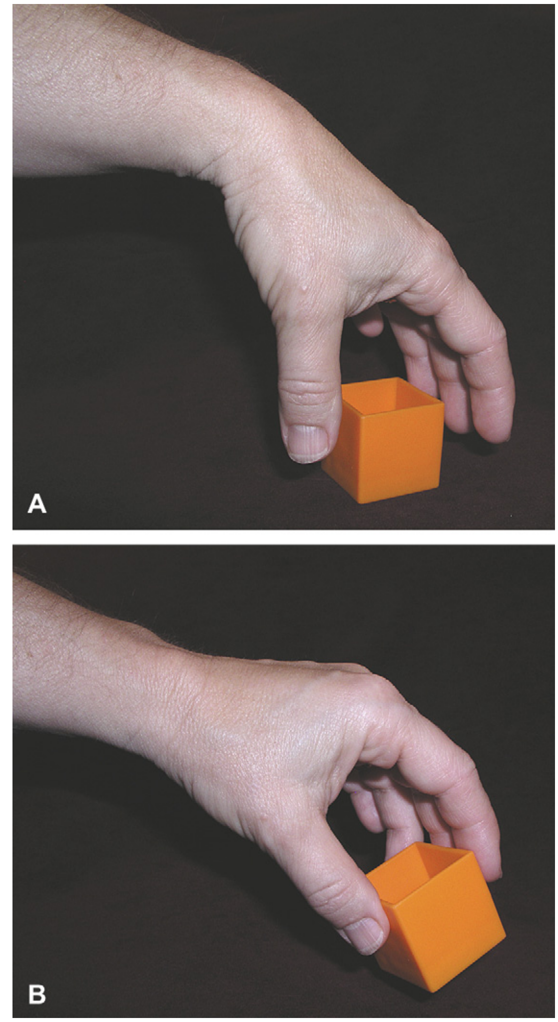

FIGURE 2. *(**A**) Wrist flexes and fingers extend during the approach phase. (**B**) Wrist extends and fingers flex during the grasp phase.*

approach grasp, and release functions. The inability to extend the finger MCP joints and thumb interferes with grasping large objects (Figures 2A and 2B). These impairments greatly interfere with hand function.

The perpetual wrist drop position creates tension through the denervated extensor muscles causing them to elongate. Conversely, the innervated, unopposed flexor muscles are slack, causing them to shorten, resulting in reduced joint mobility.[8,9] Thus, if and when the extensors are reinnervated, joint flexion contractures and extensor active insufficiency[10] will greatly impede functional motion. In addition, the absence of joint motion adversely affects the long-term health of articular cartilage, promoting malnutrition and early degenerative joint changes.[11]

Classification of Peripheral Nerve Injury

Severity of peripheral nerve injury is categorized according to the degree of internal damage to the nerve, using either Seddon's classification of neuropraxia, axonotmesis, and neurotmesis, or Sutherland's five-degree classification.[3]

Sutherland's first-degree corresponds to Seddon's neuropraxia, which is a temporary loss of axonal conduction with excellent prognosis for complete spontaneous recovery within six weeks. Second degree compares with Seddon's axonotmesis, involving the axon and myelin but with intact endoneurium, thus excellent prognosis for complete, spontaneous recovery within a few months. Third degree corresponds to Seddon's axonotmesis, involving the axon, myelin and endoneurium, but with intact perineurium. Recovery usually occurs within six months, although regeneration is usually incomplete. Fourth degree is a neuroma in continuity, where there is extensive internal nerve damage with connective tissue scarring, but the epineurium is still intact. Residual deficits occur due to varying degrees of faulty reinnervation or failed regeneration. Sutherland's fifth degree corresponds to Seddon's neurotmesis, which is a transected nerve in which none of the connective tissue elements are intact. Disruption of the axon and all the connective tissue components requires surgical repair and residual deficits result from varying degrees of faulty reinnervation, failed regeneration, or scar tissue. MacKinnon and Dellon added a sixth degree to the classification system, which is any combination of the above injuries.[12]

Classification of Radial Nerve Injury

In addition to the Sutherland and Seddon classifications, Lowe et al. classified radial nerve injury according to its level along the path of the nerve—low, intermediate, and high (Table 1).[3] A low radial nerve injury occurs at or distal to the elbow, involving one or both of the terminal branches. Injury to the DSRN affects dorsal hand sensation and nerve irritation can cause pain.[3] Fortunately, the area of anesthesia is not on the palmar surface of the hand so sensory loss itself does not usually impair hand function. Injury to the PIN causes weakness or paralysis of the muscles distal to the injury site innervated by that nerve. Wrist extension is weakened, but not entirely lost due to intact innervation to 1) the extensor carpi radialis longus (innervated more proximally) and 2) sometimes also to the extensor carpi radialis brevis (which can be innervated by the radial nerve, PIN, or even the DSRN).[13]

An intermediate injury occurs between the insertion of the pectoralis muscle and the terminal branches of the radial nerve, thus affecting both the PIN and DSRN and innervation to the remaining wrist extensors.[3] Humeral fractures and elbow injuries generally result in an intermediate-level injury.

A high injury occurs proximal to the level of insertion of the pectoralis major muscle on the humerus and all radial nerve function is impaired. Thus, in addition to damage at the intermediate level, the triceps and anconeus are also affected.

Remaining Motor Function

Despite paralysis of the brachioradialis, elbow flexion is fairly strong due to intact function of the biceps brachii and the brachialis, which are innervated by the musculocutaneous nerve. Supination is only weakened due to intact function of the biceps brachii, which can generate a strong supination force.

TABLE 1. **Motor Impact of Radial Nerve Injury at Different Levels**

Level of Injury			*Muscles Affected*	*Consequences of Muscle Paralysis*
High injury			• Triceps • Anconeus	Loss of elbow extension
			• Brachioradialis	Slightly weakened elbow flexion Weakened forearm rotation
	Intermediate injury	Low injury/ posterior interosseous nerve	• Extensor carpi radialis longus • Extensor carpi radialis brevis • Extensor carpi ulnaris	Weakened wrist extension Weakened wrist radial and ulnar deviation
			• Supinator	Weakened forearm supination
			• Extensor digitorum • Extensor digiti minimi • Extensor indicus	Further weakened wrist extension Loss of finger MCP extension Weakened IP extension
			• Abductor pollicus brevis	Loss of thumb carpometacarpal radial abduction Wrist radial deviation further weakened
			• Extensor pollicis longus	Loss of thumb IP extension
			• Extensor pollicus brevis	Loss of thumb MCP extension Wrist radial deviation further weakened

Muscle paralysis causes atrophy in dorsal and radial sides of forearm.

MCP = metacarpalphalangeal joint; IP = interphalangeal joint.

Palmar abduction is unaffected due to intact function of the abductor pollicis brevis, which is median nerve innervated. Because the median and ulnar nerves innervate the lumbricals and interossei, there is usually only some weakness of finger IP extension.

Prognosis for Recovery

Axons in the peripheral nervous system have the capacity to regenerate and, under optimal circumstances, reestablish contact with the appropriate end organs—motor endplates or sensory receptors—thus restoring motor and sensory innervation. As a general rule, regenerating axons grow at the rate of about 1 mm per day or about 1 in per month.[14]

As the radial nerve regenerates, motor supply is restored (to varying degrees) from proximal to distal, following the path depicted in Figure 1 and Table 1, unless there is anomalous innervation. Thus, more proximal muscles will be reinnervated before more distal muscles. Sensory and sympathetic innervations are also restored to varying degrees.

If regenerating motor axons do not reestablish contact with the motor endplates in the muscle within 12 to 18 months, the motor endplates will degenerate and motor function will not be fully restored.[12,15] Thus, the higher the level of nerve injury, the further the regenerating axons need to grow and the poorer the prognosis for the more distal muscles to become functionally reinnervated.

Similarly, the various encapsulated sensory receptors in the skin—Meissner corpuscle, Merkel cell neurite complex, Pacinian corpuscle, Ruffini corpuscle complex—have limited capacity for survival without axonal contact.[14] Thus, some of them may have degenerated by the time the axons have grown sufficiently to reestablish innervation.

The prognosis for recovery also depends on the extent of connective tissue damage. First- and second-degree injuries are expected to eventually recover full sensory and motor function because all connective tissue components are intact and undamaged. Third-, fourth-, fifth-, and sixth-degree injuries typically result in incomplete or failed reinnervation due to connective tissue injury and internal nerve scarring.[3,14]

Orthotic Intervention

Orthotic intervention (splinting) for radial nerve paralysis should address both the functional (occupational) needs of the patient and biological needs of the tissues (Table 2).

A static volar wrist-hand splint is commonly provided for night use to optimally position the wrist, thumb, and fingers and to prevent contractures.[16–18]

For daytime function, a range of orthotic designs has been documented.[18] They vary according to the number of joints incorporated (wrist only; wrist and fingers; wrist, fingers, and thumb; fingers and thumb) and the force system used (static, tenodesis, or dynamic). Static splints support the wrist alone and can be volar, dorsal, or circumferential.[18,19] They can be either custom-made or prefabricated.

TABLE 2. Occupational and Biological Objectives of Orthotic Intervention for Upper-Extremity Peripheral Nerve Lesions

- Enhance hand dexterity by compensating for weak/paralyzed muscles
- Prevent overstretching of denervated muscles
- Prevent shortening of unopposed innervated muscles
- Prevent joint contractures
- Maintain tendon and nerve glide
- Enable joint motion to optimize joint cartilage nutrition and health
- Prevent the development of maladaptive compensatory/substitution prehension patterns
- Keep surgically repaired nerve(s) slack to prevent tension that could interfere with nerve healing at suture site
- Prevent joint positions/motions that could aggravate a compressed nerve
- Decrease pain and paresthesia caused by nerve entrapment

Dynamic splints use energy-storing materials, such as elastic, springs, or spring wire, to pull affected joint(s) in one direction while allowing active-resisted movement in the opposite direction of the dynamic force. The most commonly-provided orthotic design for high or intermediate radial nerve paralysis is composed of a static support for the wrist (across the palmar arch), whereas the fingers and thumb have dynamic extension assists via cuffs around the proximal phalanges[18,20–25] Other designs provide dynamic extension assistance to the fingers, thumb, and wrist.[18,24–28]

The provision of dynamic extension power generally requires an outrigger, formed from either wire or thermoplastic, that projects above the dorsal surface of the hand for the fingers and above the radial surface for the thumb. Construction of such an outrigger often requires arduous wire cutting and bending and very secure attachment to the dorsal forearm base. Alternatively, either prefabricated components or fully prefabricated splints can be used.[29,30] Only one fully custom-made splint, the Rogers splint, was found that provided dynamic extension assistance to the MCPs without a projecting outrigger.[22] Dynamic extension assistance can be provided to the wrist alone using prefabricated components such as joint-aligned coil springs[25], Phoenix™ wrist hinges, or Rolyan® dynamic spring wrist hinges.[29,30]

Tenodesis splints harness active wrist flexion to produce passive finger MCP extension and conversely harness active MCP flexion to produce passive wrist extension.[8,25,31,32] An advantage of tenodesis splints over dynamic splints is that tenodesis metal components closely follow the contours of the hand, thus taking up less space. However, drawbacks are 1) the finger MCPs flex or extend as a unit, thus independent MCP motion is not possible; 2) the thumb is often excluded unless a separate dynamic component is added; and 3) the entire weight of the hand is suspended from cuffs around the finger proximal phalanges, which can be fatiguing for continuous daytime use.

High- and intermediate-level radial nerve injuries require a forearm-based splint because the wrist needs support. A low-level injury, involving only the PIN, may not require wrist support/assistance and a hand-based design, which provides dynamic finger and thumb extension assistance, may suffice. Similarly, in a high-level injury when the radial nerve has regenerated sufficiently to restore wrist extension power, a hand-based design can be substituted for a forearm-based design.[17,18,24,25]

Prefabricated Orthoses and Orthotic Components

Prefabricated metal components are available through AliMed,[33] North Coast Medical,[29] Sammons Preston Rolyan,[30] and others. Outrigger tubes, transmitting covered elastic cord, have also been incorporated into some designs.[29,30,34]

The Robinson Hand-Based Radial Nerve Splint, a prefabricated splint, is a leather glove with InRigger™ technology consisting of strips of spring metal within the glove that provide extension assistance to the MCPs of the fingers and thumb.[33]

Efficacy

Hannah and Hudak[35] conducted a single-subject study of a patient who sustained a subglenoid shoulder dislocation. After a brachial plexopathy, she experienced full recovery of the biceps, triceps, supinator, and pronator teres muscles but residual impairments included lack of wrist, finger, and thumb extension (i.e., radial nerve palsy). Their study examined hand function and patient preference, comparing three orthotic designs—1) static volar wrist, 2) dorsal forearm-based dynamic finger and thumb MCP assistive extension, and 3) dorsal forearm-based tenodesis with dynamic thumb assistive extension. Three standardized functional outcome measures showed that both the dynamic and tenodesis splints enabled statistically significant improved hand function, whereas the static volar wrist splint did not. When given the option, the patient never used the tenodesis splint 3) and she used the static volar wrist splint 1) more often than the dynamic splint 2) because it provided support and was less conspicuous. Thus, some patients may prefer to sacrifice better hand function for a splint that draws less attention.

Alsancak[24] explored satisfaction among 83 subjects with radial nerve injury who were fitted with dorsal dynamic wrist-hand splints. All patients were very satisfied with the support, functionality, and ease of donning/doffing, but were dissatisfied with the appearance until the design was modified to a lower profile style that was more streamlined and closer to the hand.

Ideally then, a splint for high radial nerve injury should:

- Provide dynamic power to the wrist, thumb, and fingers while permitting independent finger motion
- Maintain optimal length of muscle/tendon units and joint capsules/ligament
- Be low-profile (as close to hand as possible), thus less conspicuous and taking up less space than a high profile design
- Be easy to don and doff
- Be durable for long time use (i.e., several months)
- Be easy to adjust (if necessary), maintain and keep clean
- Be lightweight to prevent proximal muscle fatigue
- Be comfortable—absence of pressure points, minimal sweating, no skin irritation
- Be easy to construct—avoids wire bending/cutting if possible
- Be cosmetically acceptable to the patient

CASE REPORT

Mrs. M., a 76-year-old, retired bank worker, had a lengthy history of osteoarthritis and osteoporosis. She lived with her husband and both were in fairly good health. During elective surgery for right (dominant side) total shoulder replacement surgery (Delta Reverse), she sustained a proximal nerve injury. As customary for acute nerve injuries, electromyographic (EMG) assessment was deferred until two months post-injury. Functionally, Mrs. M. could not extend her elbow, fingers, or thumb; the posterior of her hand, forearm, and arm were numb; also shoulder elevation and wrist extension were extremely weak (Figure 3).

Before discharge, she was initially fitted with a low-profile dorsal dynamic forearm-based finger-MCP assistive-extension splint for daytime use (Figure 4), and a volar wrist-hand splint for night use (Figure 5). Both were molded from 1/8 in (3.2 mm) thick unperforated low temperature thermoplastic (LTT) and worn over a stockinette sleeve.

Two months postinjury, Mrs. M. was seen for follow-up and reported that her dynamic splint was heavy and hot to wear and caused pressure points over the ulnar and metacarpal heads. She rated her hand function as 0% because the splint did not provide sufficient finger extension assistance, fine motor control, and lacked thumb extension/abduction assistance. She identified five important

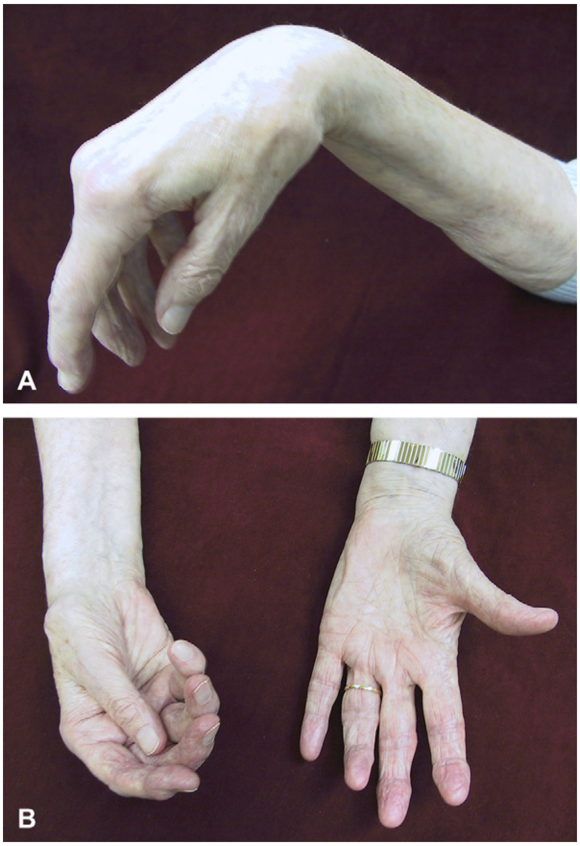

*FIGURE 3. Posture of Mrs. M.'s hand two months post-injury. (**A**) Wrist and finger drop. (**B**) Attitude of right hand with radial nerve paralysis compared to left unaffected hand. Note the flexed position of the fingers and the adducted position of the thumb.*

activities that wanted her to do but could not do with this initial splint: use cutlery, brush her teeth, write, dress herself, and drive a car. She was fully dependent on her husband for assistance in these and any other activity requiring dominant hand function.

EMG at this time indicated that the level of injury was at the teres major muscle or more proximally in the superior trunk of the brachial plexus. There was severe weakness of shoulder external rotation and abduction due to marked denervation (reduc +++) of the infraspinatus muscle (suprascapular nerve impairment) and moderate denervation (reduc ++) of the deltoid muscle (axillary nerve impairment). More significantly, severe axonal loss in the radial nerve distribution resulted in no triceps function (reduc +++), absent brachioradialis, only slight wrist extension, and complete "finger drop" (Figure 3). The nerve appeared to be in continuity but with axonal deterioration. Mrs. M. was told that recovery could take 24 to 30 months.

Although median and ulnar nerve conduction was normal, finger IP extension was weaker than usual for radial nerve injury. Thus, the neurologist recommended a revised orthotic design positioning the finger cuffs around the middle, rather than the proximal, phalanges to assist proximal interphalangeal (PIP) joint extension.

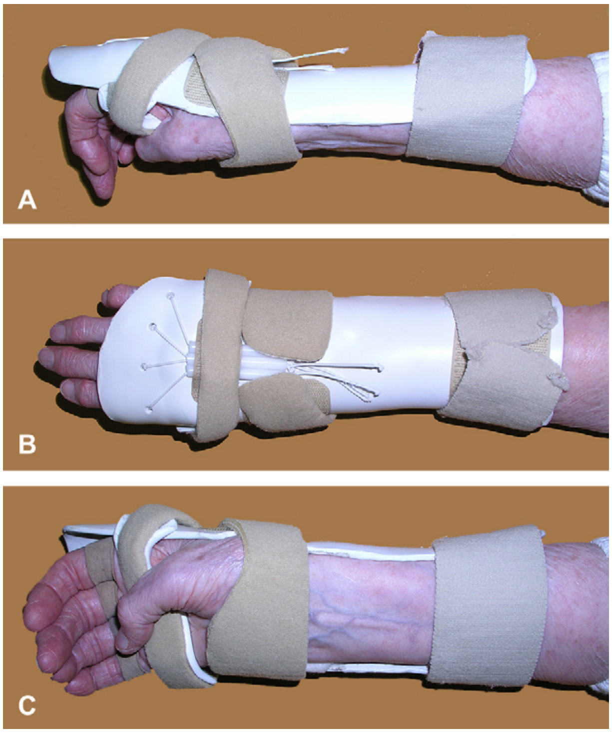

*FIGURE 4. Dorsal dynamic forearm-based finger-metacarpalphalangeal joint assistive-extension splint. (**A**) radial, (**B**) dorsal, (**C**) volar.*

Orthotic Goals

The goals of orthotic intervention were to develop a regimen that met Mrs. M.'s occupational/functional and biological requirements (Table 3) and also suited her specific cognitive, emotional, and physical capability as well as her specific environmental circumstances. More specifically, it was important for Mrs. M. that her new splint would enable her to regain independence using cutlery, brushing teeth, writing, dressing, and driving a car.

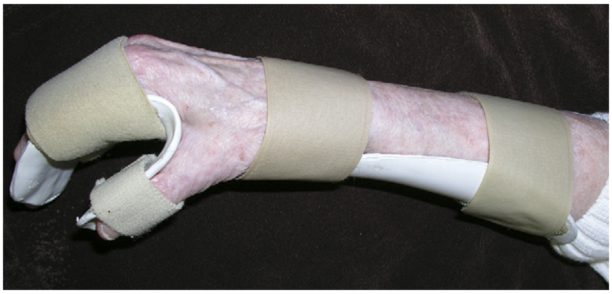

FIGURE 5. Original volar static wrist-hand splint made from 1/8 in (3.2 mm) thick thermoplastic. The replacement splint (not shown) positioned the wrist in more extension.

TABLE 3. **Mrs. M.'s Orthotic Requirements**

Addressing occupational goals/concerns:
• Compensate for lack of active wrist, finger, and thumb extension until muscles were reinnervated
• Enable tasks important to Mrs. M.—using cutlery, brushing teeth, writing, dressing, and driving a car
• Minimize occupational hindrance—easy to use and maintain
• Modify the orthotic design in keeping with progressive reinnervation of muscles, thereby avoiding further unnecessary occupational hindrance
Addressing biological goals/concerns
• Prevent contractures of thumb web space and innervated flexor muscles and subsequent flexion contractures of wrist and fingers
• Prevent overstretching of paralyzed extensor muscles
• Prevent sustained traction (causing adverse neural tension) on the regenerating radial nerve[37]
• Promote joint movement to maintain nerve excursion to prevent adherence to surrounding tissues
• Although radial nerve regeneration was anticipated, there was concern that denervated extensor muscles would not become reinnervated soon enough to preserve motor endplate viability
• Preserve integrity of fragile, thin, elder skin, especially in areas that lacked sensation
• Prevent undue stress to weakened proximal muscles and joints due to the weight of splints and restricted wrist motion
• Prevent undue stress to contralateral, osteoarthritic hand when applying and removing splints
• Provide stabilization to lax thumb joints
• Prevent fatigue of partially reinnervated muscles
• Modify the orthotic design in keeping with progressive reinnervation of muscles.

Splint Design and Fabrication

Considering her experience with the first dynamic splint and her specific orthotic requirements (Table 3), a low-profile dorsal dynamic forearm-based assistive-extension splint was constructed using 1/12 in (2 mm) thick mini-perforated uncoated LTT (Figure 6). This thickness was selected to minimize the weight of the splint, considering her recent shoulder surgery and proximal muscle weakness due to the nerve injury.

Before molding, a stretchy, washable fabric was bonded to the dry-heated LTT to create a comfortable lining (Figure 6C), using a technique developed by Margareta Persson of Sweden (unpublished, 2004). Plastazote® padding was applied to the skin over the dorsal wrist and metacarpal heads before molding, then transferred to the inside of the splint after molding. (Figure 6C). A suede finger cuff around each middle phalanx was tied to a covered elastic cord, which was routed through holes in the LTT base and then through thermoplastic tubes (Figure 6D). Tension adjustment was achieved with a separate length of elastic as shown in Figure 6E using a girth hitch knot suggested by Van Lede.[36] This splint was initially too short distally, causing the finger cuffs to slide proximally during flexion. To correct this, a thermoplastic extension was bonded to the distal end of the splint (Figure 6D).

A piece of LTT was dry heated, bonded to the palmar loop Velcro® strap, and then molded to conform to the palmar curves of the hand, to provide optimal hand support (Figure 6F).

Hyperextension instability of Mrs. M.'s thumb MCP posed a challenge when addressing the need for thumb extension/abduction assistance (Figure 7A). Trial and error led to the fabrication of a separate unlined circumferential thumb piece. It was secured to the forearm base with a strip of elastic Velcro®, which quickly wore out and was replaced with more durable standard loop Velcro®, which proved to be just as effective (Figures 6D, 7B, and 7C). The thumb piece stabilized the MCP joint while providing dynamic extension/abduction assistance.

Without the thumb piece, her thumb lacked any opposition function. With the joint-stabilizing dynamic assistance of the thumb piece, she had functional pinch and gross grasp. She regained the ability to use a cup, pen, key, and pick up paper. Mrs. M. stated that the thumb piece allowed her to "eat properly with utensils instead of shoving food into my mouth."

The original static volar wrist-hand splint was replaced with one molded from the same 1/12 in (2 mm) thick LTT, worn over stockinette at night.

RESULTS

Mrs. M. appreciated the lighter weight of both the dynamic day splint and the static night splint, noting that it was much easier to move her arm due to the reduced stress on her operated shoulder and weak proximal muscles. She was also pleased with the finger extension assistance and the comfortable bonded lining that eliminated the need to wear stockinette during the day. From Mrs. M.'s perspective, her improved thumb function was especially appreciated. In her own words: "The thumb piece was the most important thing—if your thumb doesn't work, how do you hold something at all!?"

Unexpectedly, the LTT proved thin enough to bend, thus allowing active wrist flexion, yet with sufficient rebound to pull the wrist back to a neutral position, which endowed the splint with a dynamic wrist extension function, another new feature which Mrs. M. really appreciated (Figure 8). Thus, considering the improved functional capacity enabled by the new splint, it can be described as a *low-profile dorsal dynamic wrist-finger-thumb assistive-extension splint*. Directions for fabricating the splint are provided in McKee and Nguyen (in this issue, pp. 70–72).

Difficulty slipping the limp suede finger cuffs over the fingers was addressed by lining the cuffs with

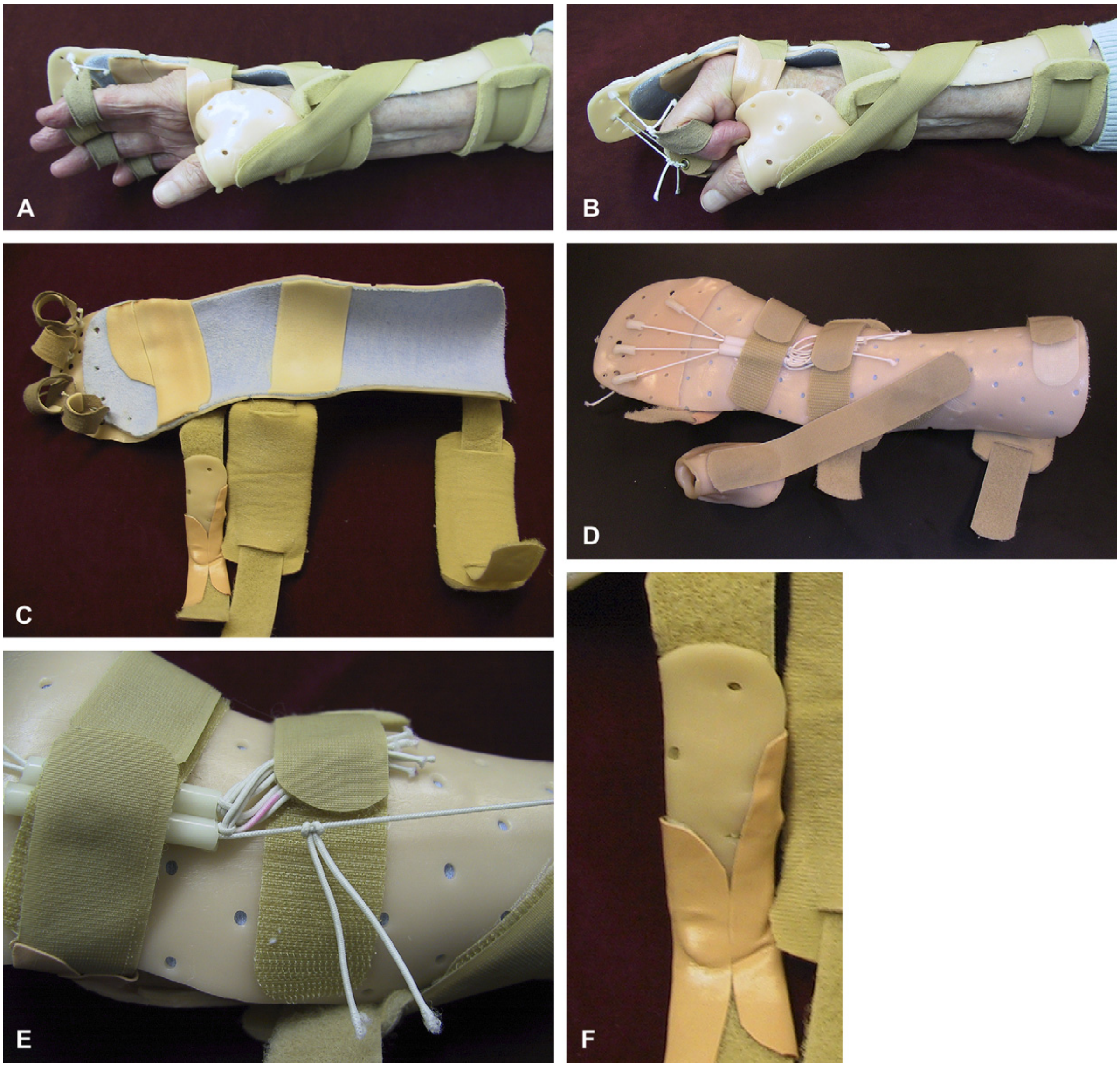

*FIGURE 6. Low-profile dorsal dynamic wrist-finger-thumb assistive-extension splint molded from 1/12 in (2 mm) thick Redifit Classic (similar to Orfit Classic). (**A**) Relaxed extended position of joints achieved by splint. (**B**) Unrestricted active finger flexion. (**C**) Volar view showing self-adhesive Plastozote® padding adjacent to dorsal wrist and metacarpal heads, bonded fabric lining, and padded forearm straps. (**D**) Dorsal view showing elastic cords passing dorsally through holes lined with Aquatubes® to prevent fraying of cord, then through two Aquatubes® over dorsal hand; the thumb piece is attached to the forearm base with standard loop Velcro®. (**E**) Elastic tension adjuster. (**F**) Palmar strap with bonded, thermoplastic contoured to the transverse palmar arch. Thin waterproof, foam tape covers some of the edges.*

1/16 in (1.6 mm) thick Plastozote® that provided sufficient stiffening to prevent them from collapsing (Figure 9), which facilitated donning the cuffs.

Mrs. M. wore the dynamic wrist-hand splint throughout the day for all activities of daily living. Once she was accustomed to the new splint, she rated her hand function at 70% of its preinjury level. Active range of motion exercises and electric stimulation were also part of her comprehensive hand therapy program.

With improved dynamic extension for the wrist, fingers, and thumb, and some assistive devices, Mrs. M. was now able to accomplish four out of her five occupational goals. She was able to use cutlery with custom-made built-up handles made from thermoplastic pellets (Figure 10A), brush her teeth, write with built-up pens (Figure 10B), and she had the strength and dexterity to pull up her slacks. Her affected hand was able to function again as her dominant hand and videographic documentation showed that bilateral activities, such as fastening buttons, were performed with natural movements of all joints (including the wrist) and with normal speed.

However, Mrs. M. remained unable to drive because the splint prevented her from getting her hand close enough to put the key into the ignition slot. A

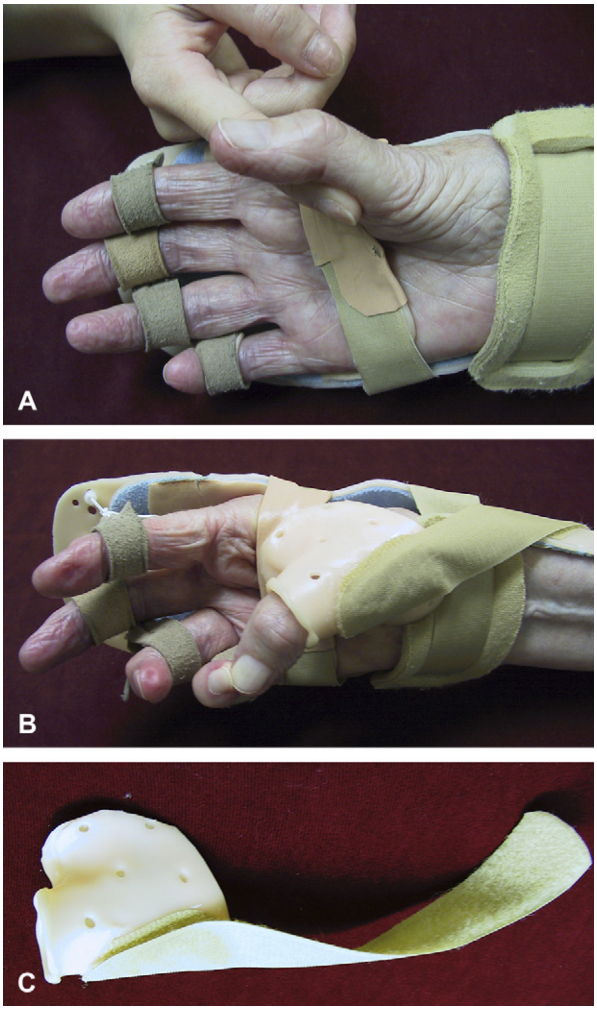

*FIGURE 7. Addressing thumb instability. (**A**) Demonstration of thumb metacarpalphalangeal instability and close-up view of suede cuffs around the middle phalanges. (**B**) Thumb piece that permitted active thumb opposition and provided extension assistance. (**C**) Thermoplastic thumb component with standard loop Velcro® strap.*

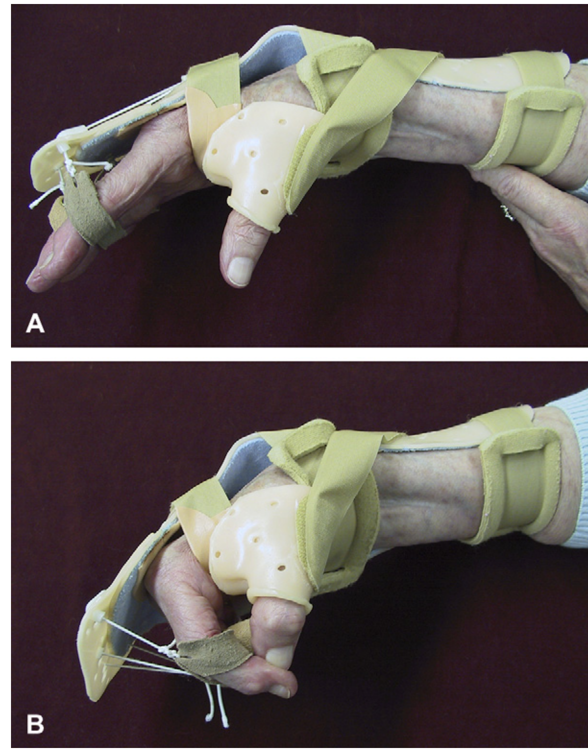

*FIGURE 8. Wrist mobility. (**A**) Active wrist flexion with passive finger and thumb extension. (**B**) Unrestricted active wrist and finger flexion.*

prefabricated Robinson Hand-Based Radial Nerve Splint was obtained, but it proved to be too bulky and heavy and did not provide the level of function she required. An alternate solution was explored and she subsequently purchased an adapted key turner, which extended her reach sufficiently to enable her to put her key in the ignition and thus drive her car (Figure 10C).

> *I got so frustrated and upset before I got the new splint—nothing worked. But with it, I learned to print and then write; I can brush my teeth and drive my car. I can't imagine not having it.*

Modification of Orthotic Design with Progressive Reinnervation of Muscles

At eight months postinjury, shoulder and elbow muscles showed good reinnervation and grade 3+ wrist extension was observed. Subsequently, a *dorsal hand-based dynamic finger-thumb assistive-extension splint* was fabricated to encourage the use and strengthening of the wrist extensors (Figure 11). As before, fabric was bonded to 1/12 in (2 mm) thick LTT and a separate thumb piece was fabricated. At this point, Mrs. M. rated her hand function at 80% of its preinjury level.

She alternated between the two daytime splints, depending on the activity she was doing and the level of muscle fatigue that she experienced. She expressed great pride in her ability to wrap Christmas presents independently because she could cut and fold the paper, apply adhesive tape and write the labels. At about this time, Mrs. M. discontinued using the volar wrist-hand splint at night.

At 13 months post-injury, grade 4 extension had returned to the wrist and active extension was observed in the finger MCP and IP joints. Mrs. M. was able to function without a splint for periods during the day, although her muscles fatigued quickly, causing aching in the dorsal forearm. She was advised to use pain as a guide to prevent fatigue to the muscles that were becoming reinnervated and to return to using a splint at the first sign of fatigue.

By 15 months postinjury, Mrs. M. used either the hand-based dynamic splint or nothing at all. At 17 months, the final EMG revealed continued minor denervation of the finger extensors and long abductors of the thumb and absent DRSN function (Figure 12). Thumb weakness and hyperextension

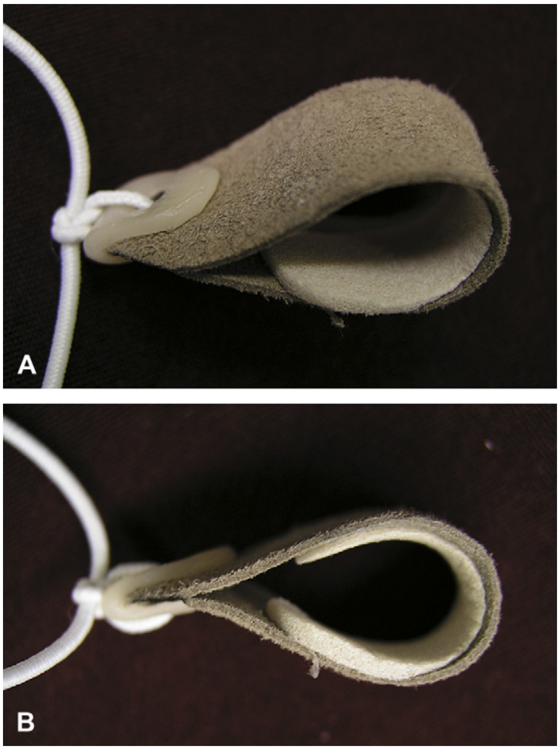

FIGURE 9. *Suede finger cuffs. 1/16 in (1.6 mm) thick Plastazote® adhered to the inside of the finger cuff to facilitate sliding over finger. Thermoplastic reinforcement over the hole prevented the elastic cord from tearing through the suede material.*

of the thumb MCP joint, along with poor sensation, still interfered with prehension and she complained of clumsiness causing her to drop objects when she was not wearing any splint. To address these functional concerns, a *circumferential hand-based thumb MCP-stabilizing splint* (with pull-back strap) was molded from uncoated 1/16 in (1.6 mm) LTT (Figure 13). To protect her thin, hypersensitive skin and bony prominences, thin neoprene—1/16 in (1.6 mm)—was bonded to the dry-heated LTT before molding. Mrs. M. kept the lined splint clean with Mirazyme, an odor-eliminating cleanser for neoprene. She was advised to use muscle fatigue as an indicator to return to using the hand-based dynamic splint.

At 23 months post-injury, Mrs. M. met with a hand surgeon to explore the possibility of surgical joint stabilization for her thumb so that she could discontinue the use of the thumb splint. The surgeon's conclusion was that because she had no thumb pain, surgery would not increase her hand function and that she should instead use the thumb splint indefinitely.

At 27 months post-injury, Mrs. M. was wearing the thumb splint most of the time and she was able to perform activities such as dusting, raking leaves, and watering her garden with a hose. She managed without any splint during short periods of time in the morning and evening when she is performing personal hygiene tasks such as brushing her hair, washing her face, brushing her teeth, getting dressed/undressed, and putting on her lipstick. She used the hand-based dynamic splint only when she went out to eat, preferring to use restaurant utensils rather than her own utensils with built-up handles.

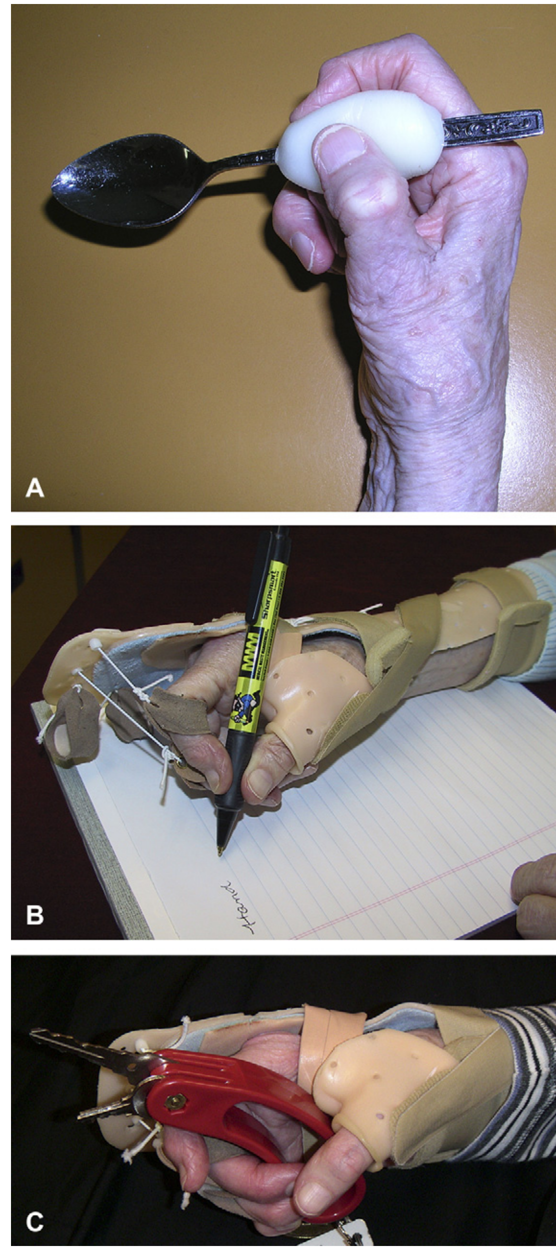

FIGURE 10. *Enabled tasks. (**A**) Grasping a spoon with a handle built-up with thermoplastic pellets. (**B**) Hand writing enabled with the splint. Note that the cuffs were slid off the ring and small fingers for this task. (**C**) Key holder that enabled reaching the ignition slot of the car.*

She continued to have difficulty with some fine dexterity tasks such as sewing with a needle and thread, and applying and fastening jewelry, which she attributed to poor sensation in the tips of her thumb and index. However, overall she was very

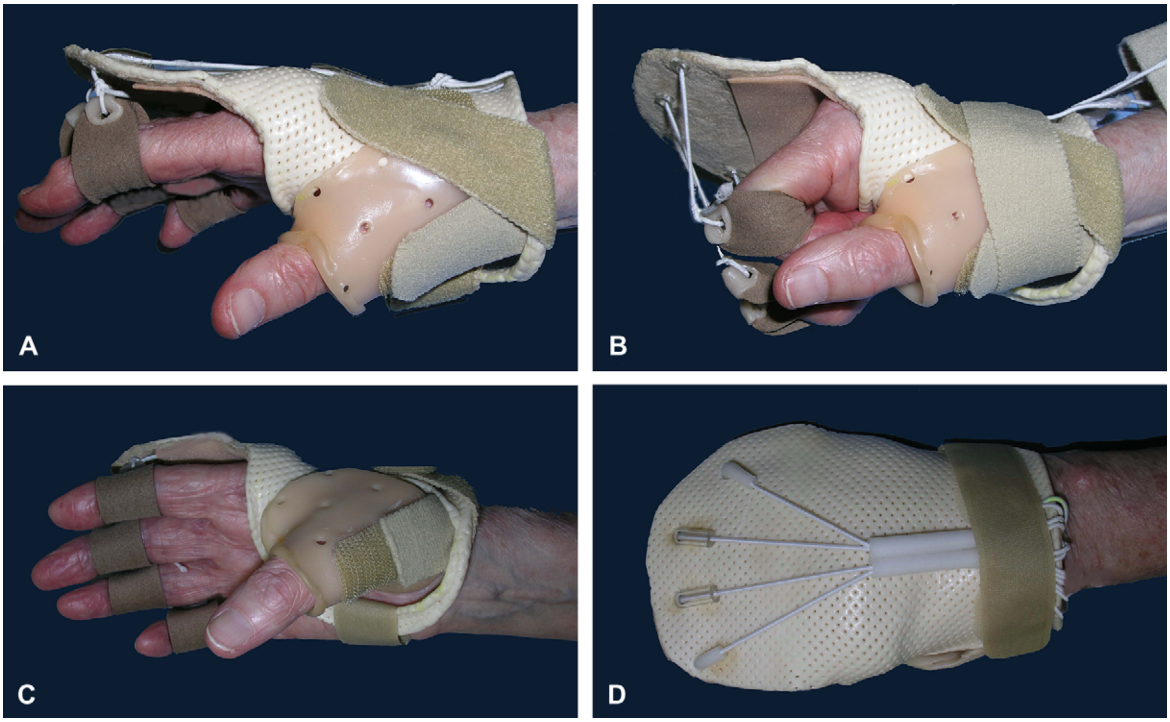

FIGURE 11. Low-profile dorsal hand-based dynamic finger-thumb splint. Stretchy velor fabric was bonded to 1/12 in (2 mm) thick micro-perforated low temperature thermoplastic (LTT) (specifically Orfilight®) and with Plastazote® padding was adjacent to the metacarpal heads. As with the dynamic forearm-based splint, a separate thumb piece was made from 1/12 in (2 mm) thick low temperature thermoplastic. For this splint, elastic Velcro® was used. (A) Relaxed extended position of joints achieved by splint. (B) Unrestricted active finger and thumb flexion. (C) Volar-radial view. (D) Dorsal view showing elastic cords passing dorsally through tube-lined holes in splint, then through two Aquatubes® over dorsal hand.

satisfied with her level of independent function. She rated her hand function at 85% with a splint and 50% without a splint.

Mrs. M. stated:

> *If I hadn't got those splints, I'm sure I wouldn't be using the hand at all. I wouldn't be what I am today without them. Without my hand therapists, I would never have got through this.*

DISCUSSION

Mrs. M. had a high radial nerve injury, caused by an undetermined intraoperative mechanism of injury. Recovery over 27 months was documented, during frequent clinic visits, by patient report, muscle testing, EMG, photography, and videography. The use of a standardized functional outcome measure would have further enhanced this account.[35]

At two months postinjury, the neurologist predicted that it would take 24 to 30 months for the nerve to fully regenerate, which is beyond 12 to 18 months that motor endplates are expected to remain viable.[12,15] Although full return of function was not achieved, radial nerve recovery progressed very well, despite her advanced age and the long distance that the axons needed to regenerate. The final electromyography at 17 months showed only minor residual denervation of the finger extensors and long abductors of the thumb, the most distal muscles along the course of the radial nerve (Figure 1).

The dynamic splints permitted mobility of all her joints, which enabled and prevented adverse neural tension,[37] which would likely have been the case if the wrist drop posture had not been addressed. Nerve mobility is desirable 1) to prevent nerve adherence to the tissues that it travels through and 2) to enable intraneural glide of fascicles.[14] At 27 months postinjury, Mrs. M. could function without a splint if need be, although she often wore the hand-based thumb-stabilizing splint to compensate for continued thumb weakness, and joint instability caused by premorbid osteoarthritis. She also used the dynamic hand-based splint when using standard eating utensils at a restaurant. Further motor improvement was not expected due to poor prognosis for motor endplate viability beyond 18 months.[12,15]

The dynamic splints designed for this patient are unlike any previously documented designs, providing assistive-extension to the wrist, fingers, and thumb without a metal outrigger projecting above the dorsum of the hand and increasing the weight of the splint. Important functional activities that Mrs. M. valued—writing, brushing her teeth, using eating utensils dressing, driving—were fully enabled because natural patterns of motion were possible due to the ability to move all involved joints.

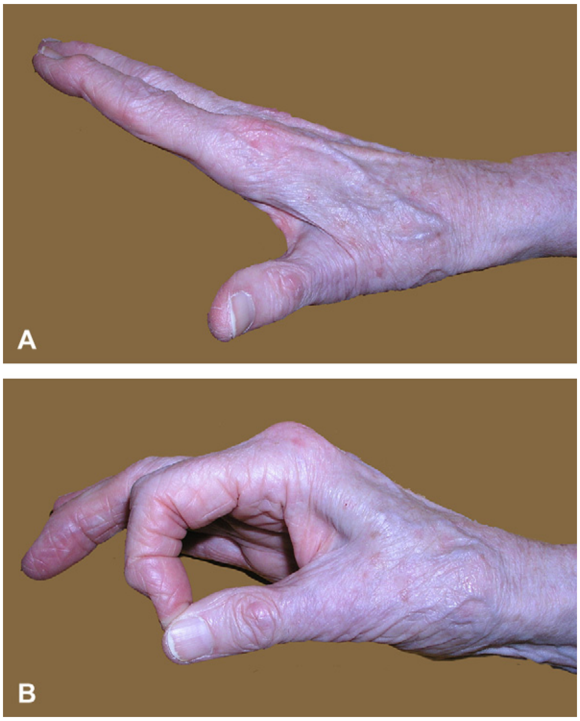

FIGURE 12. Full active range of motion of all joints achieved by 17 months postinjury.

The low profile, which enabled a large, fleece mitten to be worn over the splint during the cold winter months, was comparable to the dynamic Rogers splint[22] but with the additional dynamic wrist extension assistance. Other dynamic designs have projecting outriggers, which take up space and make the splint more conspicuous and less cosmetically acceptable to patients.[35] The low profile was also comparable to tenodesis splints that enable wrist mobility[8,31,32] but with the additional benefit of independent finger and thumb mobility.

The simple thumb component that provided abduction-extension assist—another customized feature—provided support to her unstable thumb MCP while enabling active flexion, without an outrigger that projected dorsal to the hand. The hand strap (with bonded, contoured LTT), was easy to fasten and helped to maintain the transverse arch through the palm, providing better support than a simple loop Velcro® strap. The tension adjustment mechanism was simple to make and adjust and contributed to the ease of maintenance. The patient highly valued the dynamic thumb assist, which was not provided until two months postinjury and is often excluded from tenodesis designs. Without it, her thumb lacked any abduction/extension and fell into the palm of her hand in an adducted position. With it, she could again use her thumb functionally in activities requiring pinch and grasp such as writing, using utensils, cutting with scissors, and raking leaves, to name a few. Unfortunately, a few activities (applying jewelry, hand sewing) that require discriminative sensation of the tips of her thumb and index continued to be challenging and frustrating due to persistent absence of DSRN function, which cannot be compensated for with a splint.

The flexible LTT itself provided the extension assist to the wrist without the need of cutting or bending wire. The LTT could bend to allow active wrist flexion, but had sufficient rebound to pull the wrist back to a neutral position. Several mechanical factors enabled this desirable property.

- Thin (1/12 in/2 mm thick), thus flexible LTT; for a larger hand or forceful hand tasks, a proportionately thicker LTT could be considered.
- Minimal contours over the dorsum of the wrist; contours enhance rigidity, which is undesirable at the wrist in this design.
- A relatively long flexor lever arm with the finger cuffs around the middle phalanx; when this design was replicated with another patient with radial nerve injury and the cuffs were placed around the finger proximal phalanges, active wrist flexion was not possible due to the shorter flexion lever arm.

According to Callinan[38] and Yuen Yee Chan and Chapparo,[39] daytime use of a splint that restricts wrist mobility promotes compensatory shoulder elevation that can cause harmful muscle pain and fatigue and imposes undue functional hindrance. The wrist mobility permitted by the forearm-based dynamic splint, combined with its lightweight, was especially desirable considering Mrs. M.'s recent shoulder surgery and weakened proximal muscles due to nerve damage. The weight of the splint was minimized by 1) the lack of a metal outrigger, which is characteristic of most other documented dynamic splints[8,31,32] and 2) the thin LTT. Indeed, the LTT was thinner than any previously documented dorsal forearm-based splint, yet it proved to be strong enough to suit Mrs. M.'s functional requirements. The 1/12 in (2 mm) LTT thickness was introduced in about 2000 and is only available in thermoplastics that turn translucent when heated.[18]

The ability to construct functional low-profile, lightweight dynamic splints without needing to bend or cut wire, while using relative thin, easy-to-cut LTT, has the additional benefit of avoiding injurious stress to therapists' hands.[18]

The use of uncoated LTT enabled the secure bonding of the thermoplastic extension, thermoplastic tubes, and the lining. The latter provided a comfortable interface between the LTT and the skin, without the need for a stockinette sleeve (which detracts from the overall cosmesis of the splint) to absorb perspiration. In contrast, the use of a self-adhesive lining such as moleskin would block ventilation through the perforations in the LTT. The Plastazote® padding

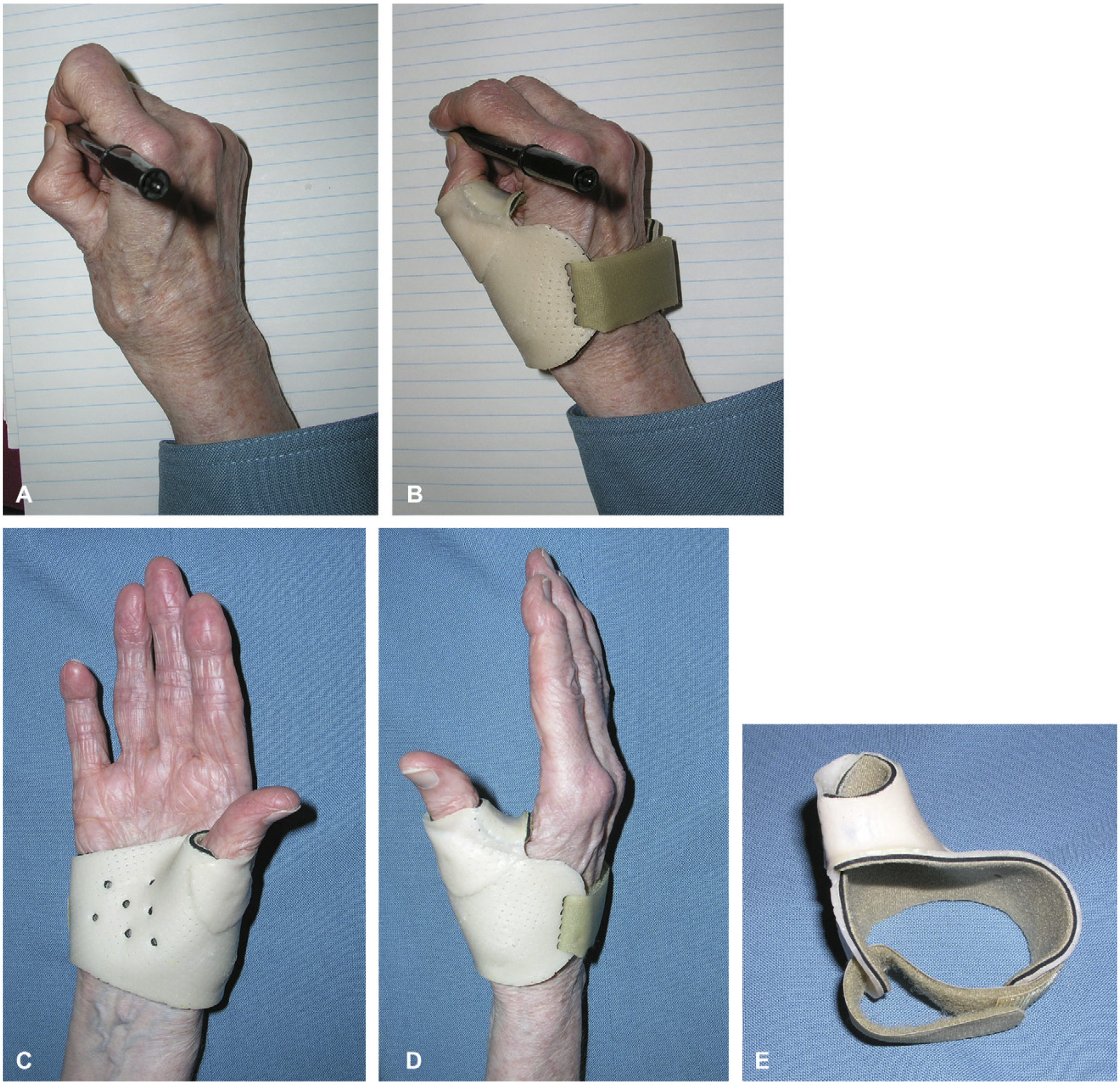

FIGURE 13. *(**A**) Thumb hyperextension instability while gripping a pen, causing poor legibility and slow writing speed. (**B**) Gripping a pen with the circumferential hand-based thumb-stabilizing splint. (**C**) Volar view showing holes punched through the material over the palm to provide ventilation. (**D**) Radial view. (**E**) Superior view of thumb splint showing 1/16 in (1.6 mm) thick neoprene lining bonded to 1/16 in (1.6 mm) thick low temperature thermoplastic and the pull-back Velcro® strap to optimize thumb carpometacarpal stabilization.*

prevented pressure on dorsal bony prominences (wrist and metacarpal heads). It was selected because it is a closed-cell foam padding and thus does not absorb moisture. Also, it is skin friendly and used in the footwear of individuals with diabetes. Thus, skin integrity was maintained without any evidence of irritation, despite Mrs. M's thin elder skin. The dynamic-lined splints were kept clean by daily cleansing with Dove® Daily Hydrating Cleansing Cloths, although other cleansing methods can be used.

As the radial nerve regenerated distally and power returned to the wrist extensors, the design features were incorporated into a hand-based dynamic splint. Eventually, a circumferential hand-based thumb splint was fabricated for activities requiring thumb stabilization but less finger dexterity; neoprene lining was incorporated to provide thin padding to protect the skin. This splint was cleaned with odor-eliminating Mirazyme cleanser.

As full active motion returned, it was apparent that the dynamic splints had 1) enabled hand function, 2) prevented flexion contractures, and 3) prevented elongation of the paralyzed extensors.[9] Fully enabled joint motion was also desirable as it helped maintain the health of the articular cartilage,[11] which in Mrs. M.'s case was already compromised by osteoarthritis.

The positive occupational and biological outcomes were further enhanced over the extended duration of orthotic intervention by frequent follow-up visits to make adjustments or repairs, modify the orthotic design and clarify how the splints should be used. Patient education enabled Mrs. M. to understand the goals of the intervention and the physiology of nerve regeneration and muscle reinnervation, thereby empowering her to actively contribute to identifying solutions.

Orthotic intervention was complimented by assistive devices to optimally enable occupations valued by the patient. The splints were cosmetically acceptable to the patient, easy to don and doff and comfortable to wear.

According to Mrs. M.'s own self-evaluation, hand function improved 1) from 0% to 70% when the initial splint was replaced with the new forearm-based dynamic splint provided at two months postinjury; 2) from 70% to 80% when the hand-based dynamic splint was introduced at eight months postinjury, when functional wrist extension had returned; 3) from 80% to 85% when the hand-based thumb-stabilizing splint was provided at 17 months postinjury, when functional finger extension had returned. At 27 months postinjury, Mrs. M. continued to rate her hand function at 85% of its preinjury function when using a splint and at 50% when not wearing a splint for activities requiring thumb stabilization. She attributed the residual 15% of hand dysfunction to the lack to sensation in the tips of her thumb and index finger.

CONCLUSION

This ''patient story,'' which spans over 27 months during the recovery of a high radial nerve injury, illustrates the importance of attending to both occupational and biological needs (Table 2), using a patient-centered, less-is-more approach,[40] with frequent follow-up.[41] Customized lightweight, low-profile dynamic splints—one forearm-based one hand-based—proved to be comfortable, convenient, and cosmetically acceptable.[24,35,41,42] They addressed the occupational/functional needs identified by the patient and the biological needs determined by the therapist.

Knowledge of 1) orthotic materials and mechanical principles, 2) biological structure, function, and healing, and 3) strategies to avoid muscle fatigue, optimize tissue length, and maintain joint cartilage health was essential to a successful outcome.

Innovative construction techniques enabled unique design features such as bonded lining, low-profile dynamic assistance without an outrigger and tension-adjustable elastic cords. These construction techniques can be transferred to other clinical situations and other orthotic designs.

The following summarizes the attributes of the low-profile dorsal dynamic wrist-finger-thumb assistive-extension splint.

- Dynamic wrist extension assistance is provided while permitting active wrist flexion due to 1) thin (1/12 in/2 mm thick) LTT, 2) lack of contours over the wrist, and 3) long lever arm—finger cuffs around the middle phalanx provide PIP joint extension assist.
- Joint motion of all affected joints is enabled, which helps to maintain the health of the articular cartilage.[11]
- Proximal muscle fatigue is avoided by 1) overall lightweight due to thin LTT and lack of metal outrigger and 2) enabled active wrist flexion, which prevents fatiguing compensatory shoulder elevation that occurs when the wrist is immobilized.[38]
- Design can be modified to exclude the forearm base (i.e., convert to hand-based design) when wrist extension does not need assistance (i.e., for PIN injury or for a high radial nerve injury when nerve re-innervation of the wrist extensors has occurred).
- Design is less conspicuous than dynamic or tenodesis splints with metal outriggers, thus more cosmetically acceptable to patients.[35]
- Design is very low profile, comparable to tenodesis designs, which also permit wrist motion.
- Independent finger and thumb mobility is enabled, unlike tenodesis designs.
- Palmar strap, reinforced with contoured thermoplastic, prevents fatigue that occurs when the hand is suspended from finger cuffs alone in tenodesis designs.
- Finger extension force is easily adjustable by the patient using simple tension adjustment of the elastic cords.
- Dynamic thumb extension assistance is provided through a simple thumb piece and Velcro® strap, without an outrigger projecting beyond the hand.
- Dynamic extension assistance is created without the need to bend or cut wire, thus avoiding injurious stress to therapists' hands.[18]
- Optional bonded fabric eliminates the need for a stockinette sleeve to absorb perspiration.

Acknowledgments

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Quiz: Article #051

Record your answers on the Return Answer Form found on the tear-out coupon at the back of this issue. There is only one best answer for each question.

#1. Which nerve is reputedly the most frequently injured nerve in the upper extremity
   a. medial
   b. radial
   c. ulnar
   d. musculocutaneous

#2. This case demonstrates the effectiveness of a therapist who
   a. was clever in designing splints from recycled materials
   b. was restricted by the cost of materials and created designs inexpensively
   c. put function ahead of comfort in designing splints
   d. was persistent in modifying splint designs in the face of a changing clinical picture

#3. The author points out that a low-level radial nerve injury may
   a. be more challenging than an intermediate-level injury
   b. involve only the PIN and hence the patient will only present with sensory, not motor, deficits
   c. involve only the PIN and hence the patient may not require wrist support
   d. be caused by a similar mechanism as occurred in this patient story

#4. Key to the success of this splint design was
   a. a forearm rotation moment and wrist stabilization component
   b. that the LTT material was lightweight and had sufficient rebound to act as a dynamic wrist extension assist
   c. PIP and DIP dynamic extension components
   d. biofeedback (tactile) via the forearm component and MP extension component

#5. Due to uncontrolled thumb MP hyperextension instability, the patient eventually underwent a surgical fusion
   a. False
   b. True

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